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ABSTRACT

Two complementary experimental techniques have been used to extract precise branching ratios to unbound states in ^{12}C from ^{12}N and ^{12}B β-decays. In the first the three α-particles emitted after β-decay are measured in coincidence in separate detectors, while in the second method ^{12}N and ^{12}B are implanted in a detector and the summed energy of the three α-particles is measured directly. For the narrow states at 7.654 MeV (0^+) and 12.71 MeV (1^+) the resulting branching ratios are both smaller than previous measurements by a factor of $\simeq 2$. The experimental results are compared to no-core shell model calculations with realistic interactions from chiral perturbation theory, and inclusion of three-nucleon forces is found to give improved agreement.

1. Introduction

The structure of ^{12}C is of long standing interest in nuclear physics. Already the low energy spectrum is believed to display a mixture of mean field and cluster structure which makes the theoretical description particularly challenging. Experimentally there are also open questions on the spectrum of states just above the 3α-threshold at 7.275 MeV. States with strong clustering can have widths $\Gamma \simeq 1$ MeV already a few MeV above the threshold and they are therefore difficult to identify experimentally due to several overlapping states in most experimental probes. Natural parity resonances, such as cluster states, in the immediate vicinity of the threshold determine the rate of the astrophysical triple-alpha reaction, most notably the 7.65 MeV 0^+ state, but also low lying 2^+ states can have a non-negligible influence.

Gamow–Teller (GT) transitions from the decays of ^{12}N and ^{12}B provide a clean probe of ^{12}C, where selection rules single out 0^+, 1^+ and 2^+ states. In addition, the strength of GT transitions are strongly dependent on the structure of the populated states. Indeed, the shell model (jj-coupled) and cluster (SU(4) symmetry) limits predict large and vanishing GT strength to ^{12}C states respectively [1]. By comparing GT transitions from ^{12}N and ^{12}B the isospin asymmetry can be tested. This is a possible test for the existence of second-class currents in the weak interaction [2,3]. However, nuclear-structure effects probably provide the principal

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contribution to this asymmetry and this observable therefore also provides a sensitive test of the nuclear structure of the populated states.

The β-decay of ^{12}N and ^{12}B to unbound states was measured in two recent experiments [4,5] focusing on the existence of 0^+ and 2^+ unbound states in the vicinity of the threshold. These transitions are difficult to measure because the branching ratios are small, and the states break up into three α-particles leading to complicated decay spectra. In [4,5] the 9–12 MeV region was described as an interference between the 7.654 MeV 0^+ state and a higher lying 0^+ state around 12 MeV, and no evidence was found for population of a low lying, astrophysically significant 2^+ state. The method applied in [4,5] excluded measurement of the 7.65 MeV first unbound state in ^{12}C due to the low energy cut-off, and therefore the interference pattern could not be fully measured. These experiments also could not provide GT strengths to the identified states due to lack of absolute normalisation.

On the theoretical side, there have been significant advances in the description of low-energy nuclear structure with the advent of *ab initio* methods, such as Green's function Monte Carlo (GFMC) [6] and the no-core shell model (NCSM) [7]. In a recent NCSM study [8] potentials from chiral perturbation theory (ChPT) were applied for the first time in the mid-p shell including three-nucleon forces (3NF). This provides a promising and long awaited bridge between nuclear structure and the underlying theory, QCD. ^{12}C is near the upper limit of the applicability of these general approaches; its ground state energy has been calculated with GFMC [6], while NCSM can also provide excited states and a range of observables [7,8]. Realistic nuclear potentials with 3NF tend to have a much stronger spin–orbit (SO) interaction which is important for mixing cluster and shell-model like structures, hence, GT transitions provide a sensitive test of these calculations. The existence of cluster structure in the low energy states of ^{12}C has also led to many studies using various built-in correlations; from three-alpha calculations to methods capable of combining cluster structure and shell-model like structure [9,10]. This cluster structure makes the description of ^{12}C a particular challenge for *ab initio* methods.

The purpose of this Letter is to provide high precision experimental GT strengths to states in ^{12}C above the 3α break-up threshold at 7.275 MeV, including the 7.65 MeV state. We use two complementary experimental approaches to determine these branching ratios. The results are compared with new state of the art NCSM calculations as well as with existing calculations using other theoretical approaches.

2. Experiments

In the first approach we use the reactions ^{12}C$(p,n)^{12}$N and ^{11}B$(d,p)^{12}$B and the Isotope Separation On-Line (ISOL) method to produce low energy beams of ^{12}N and ^{12}B and implant them in a thin carbon foil in the centre of a large solid angle, segmented Si detector array, which permits measurement of the energy and momentum of each α-particle emitted in the decays. These measurements were carried out at the IGISOL facility of the Jyväskylä Accelerator Laboratory (JYFL) [12]. The detector array consisted of three Double Sided Silicon Strip Detectors (DSSSDs) in a horseshoe formation. Each detector has 16×16 strips on an active area of 50×50 mm^2 and a thickness of 60 μm. The DSSSDs were calibrated using both online and offline sources. Offline ^{148}Gd and ^{241}Am sources were used for the energy calibration, and an online source of ^{20}Na produced in the reaction ^{24}Mg$(p,n\alpha)^{20}$Na was used both to test the energy calibration, but also to check the energy loss in the foil and detector dead layer [13]. A Ge-detector was included in the measurements to make it possible to extract absolute branching ratios and $\log ft$ values by using the known branching ratio to the 4.44 MeV state of ^{12}C and counting the number of detected 4.44 MeV gamma-rays. The same experimental method but without the Ge-detector and only two DSSSDs has previously been used in experiments at JYFL and at CERN-ISOLDE, but never measuring both ^{12}N and ^{12}B in the same setup [4,5].

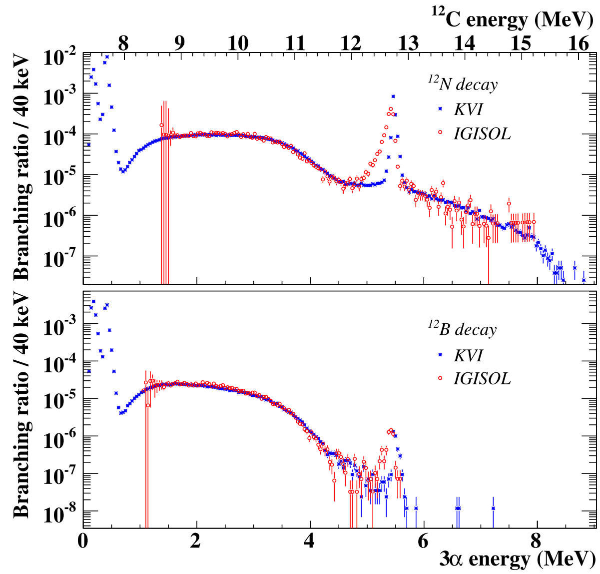

Fig. 1. Decay spectra for ^{12}N and ^{12}B from the two experiments. The branching ratio per bin, which is determined by two complementary methods in the two experiments, is shown as a function of 3α energy.

In Fig. 1 triple-alpha spectra for the decay of ^{12}N and ^{12}B are shown. These have been constructed by adding the energy of three detected α-particles, correcting for detection efficiency, and bringing to an absolute scale using the data from the Ge-detector. Note that the detection efficiency is strongly dependent on the kinematics of the break-up. Hence decays via the ^{8}Be ground state and decays through excited states in ^{8}Be are separately corrected for detection efficiency; see [14,15] for details. More than 90% of the decays of the 8–12 MeV region are via the ground state of ^{8}Be while for the 13–16 MeV region the fraction of decays via excited states in ^{8}Be is higher.

The second approach for measuring branching ratios is based on implanting the ^{12}N and ^{12}B nuclei in a detector. This experiment was performed at the Kernfysisch Versneller Instituut (KVI), Groningen. At this facility beams of ^{12}N and ^{12}B were produced using the same reactions as at JYFL, but in inverse kinematics. The separator of the TRIμP facility [16] filtered the beam for contaminants and defocused the beam to match the surface area of a 48×48 strip detector with an active area of 16×16 mm^2 [17,18]. With a detector thickness of 78 μm, α-particles from the decay of a nucleus implanted in the centre of the detector will deposit all of their energy inside the detector. The advantage of the implantation technique is that the number of implanted ^{12}N and ^{12}B nuclei can be counted, and the triple-alpha sum energy is measured directly. It is also possible to probe the spectra at very low energies, because detector deadlayer effects are avoided. The drawback is that the information about the correlations between the emitted particles is lost when only the sum energy of the emitted α-particles is measured.

The resulting decay spectra for ^{12}N and ^{12}B are also shown in Fig. 1. In this case the ordinate is simply the fraction of implantations having a subsequent decay in the same pixel of the detector.

The absolute normalizations of the JYFL data and KVI data are in good agreement in the region of overlap. The KVI data extend to

Table 1
Absolute branching ratios.

^{12}C Energy (MeV)	^{12}N Literature (%)	^{12}N JYFL (%)	^{12}N KVI (%)	^{12}B Literature (%)	^{12}B JYFL (%)	^{12}B KVI (%)
g.s.	94.6(6)[a]	–	96.03(5)	97.2(3)[a]	–	98.03(5)
4.44	1.90(3)[a]	–	–	1.28(4)[a,b]	–	–
7.65	2.7(4)[a]	–	1.41(3)	1.2(3)[c]	–	0.58(2)
9–12	0.46(15)[d]	0.38(5)	0.404(9)	0.08(2)[d]	0.060(7)	0.068(3)
12.71	0.28(8)[c]	0.11(2)	0.120(3)	–	$3.5(7)\times10^{-4}$	$2.8(2)\times10^{-4}$
12–16.3[e]	–	0.021(6)	0.020(3)	–	–	–
15.11	$3.8(8)\times10^{-3}$[c]	–	$3.2(10)\times10^{-5}\cdot\Gamma/\Gamma_\alpha$	–	–	–
7.3–16.3	3.4(4)[a]	–	2.10(3)	1.3(3)[a]	–	0.69(2)

[a] Literature values from [11].
[b] An alternative value of 1.18(2) is given in [11].
[c] Updated as described in [20].
[d] Branching ratio to the 10.3 MeV state in [11].
[e] Excluding the 12.71 MeV peak; see the text.

lower energy and include the peak corresponding to the 7.654 MeV state. The peak below this arises from energy deposition by β-particles from decays to bound states. The KVI spectra are shifted upwards by up to 50 keV compared to the JYFL spectra due to the energy deposition by β-particles. Above the 7.654 MeV peak a broad structure dominates the spectrum until the 1^+ state peak at 12.71 MeV. The 12.71 MeV peak is broader with a low energy tail in the JYFL experiment. This is caused by events where energy losses in foil and deadlayer are not fully corrected for. For ^{12}B the spectrum end point is at 13.37 MeV, while for ^{12}N another broad structure extends from the 12.71 MeV peak up to the end point at 16.3 MeV. The broad structures are the result of one or more 0^+ and 2^+ states as well as the ghost of the 7.654 MeV state [4,5,19]. It is important to notice that these structures represent states in ^{12}C populated in the decays and consequently they are not background from other sources.

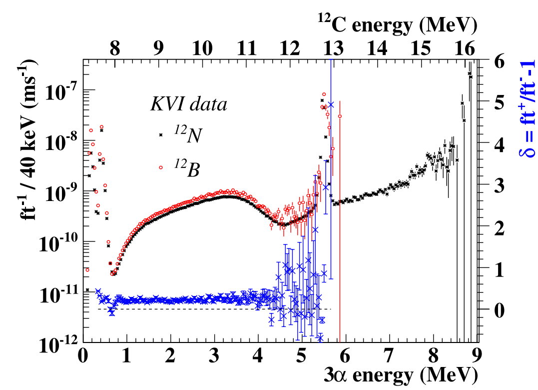

Fig. 2. Spectra of inverse ft-value per energy bin for ^{12}N and ^{12}B decays (left ordinate). The isospin asymmetry, δ, is also shown (right ordinate).

3. Branching ratios and Gamow–Teller strengths

The absolute branching ratios from the JYFL and KVI experiments are shown in Table 1 with comparison to the literature. These branching ratios are obtained from the spectra in Fig. 1 by integration. For the 12.71 MeV state a smooth background from the broad structure under the peak has been subtracted. In several cases the literature branching ratios have been updated using the measured relative branching ratios quoted in the original papers and the latest values of quantities used for normalization; see [20] for details. The two experiments yield consistent values, but with better accuracy in the KVI experiment due to better statistics and more directly determined branching ratios. New branching ratios to the ground state can be found as one minus the sum of branching ratios to all excited states (using the literature values for the 4.44 MeV state). This is the way the current literature values for the ground state branches have been obtained. This has only been done using the KVI data, since the JYFL data lack information about the low energy region. For both ^{12}N- and ^{12}B-decay the branching ratios for the 7.654 MeV state, coming only from the KVI experiment and omitting contributions from the ghost, are smaller than the literature values by a factor $\simeq 2$. A short re-measurement at KVI confirmed that this difference is not caused by e.g. a drop of detection efficiency at the low energies of the 7.654 MeV state. Branching ratios to the broad regions in the spectra are also given in Table 1. The resulting branching ratios for the 9–12 MeV region are in agreement with the literature values for the 10.3 MeV state when it is taken into account that we have excluded the contributions below 9 MeV in Table 1. The branching ratios to the 12.71 MeV state have been corrected for the small gamma branch for this state, $\Gamma_\gamma/\Gamma = 0.0222(16)$ [11]. This is the first observation of this state in the decay of ^{12}B. For ^{12}N the branching ratios are a factor of $\simeq 2.5$ smaller than the literature value. The branching ratio to the broad region at high energies (with the 12.71 MeV peak subtracted) has not previously been measured. The isobaric analogue state at 15.11 MeV has a small α branch, $\Gamma_\alpha/\Gamma = 0.041(9)$ [21], and is seen as a small peak in the ^{12}N decay spectrum with 29(9) counts. Assuming a negligible GT strength (B_{GT} value) to this state, the corresponding branching ratio leads to a Fermi strength of 0.6(2), which is inconsistent with the expected value $B_F = 2$. Accepting the theoretical Fermi strength leads to a revised value for the α width, $\Gamma_\alpha/\Gamma = 0.011(3)$, which is consistent with the value 0.012(7) in [22].

For narrow states, λ, B_{GT} values are determined from our branching ratios, BR_λ, as

$$B_{\mathrm{GT}} = \frac{g_V^2}{g_A^2}\frac{K}{ft_{1/2;\lambda}} = \frac{g_V^2}{g_A^2}\frac{K}{ft_{1/2}}BR_\lambda, \tag{1}$$

where $t_{1/2;\lambda}$ is the partial halflife of the state λ, $K = 6147(2)$ s [23], $|g_A/g_V| = 1.2695(29)$ [24], $t_{1/2}(^{12}\mathrm{N}) = 11.000(16)$ ms [11], $t_{1/2}(^{12}\mathrm{B}) = 20.20(2)$ ms [11] and f is the standard lepton phase space factor. Values are given in Table 2. For the broad regions B_{GT} values cannot be found from the branching ratios in Table 1, since f is energy dependent.

The isospin asymmetry is defined as $\delta = \frac{ft(\beta^+)}{ft(\beta^-)} - 1 = \frac{B_{\mathrm{GT}}(^{12}\mathrm{B})}{B_{\mathrm{GT}}(^{12}\mathrm{N})} - 1$ and values are given in Table 2. Isospin is a good quantum number if $\delta = 0$ corresponding to equal strengths for β^+ and β^- transitions. To give the isospin asymmetry for the broad re-

Table 2
Experimental B_{GT} values compared to NCSM results. All calculations were performed using Hamiltonians from ChPT as described in [8] with and without 3NF added. The calculations are carried out in model spaces up to $6\hbar\omega$ and $8\hbar\omega$ respectively.

^{12}C Energy (MeV)	$B_{GT}(^{12}N)$			$B_{GT}(^{12}B)$			$\delta = \frac{B_{GT}(^{12}B)}{B_{GT}(^{12}N)} - 1$
	Exp.	NN	NN + 3NF	Exp.	NN	NN + 3NF	Exp.
g.s.	0.2952(14)	0.081(20)	0.337(79)	0.331(2)	0.082(20)	0.341(81)	0.121(9)
4.44	0.0270(4)[a]	0.0050(9)	0.0054(13)	0.0297(9)[a]	0.0044(6)	0.0044(11)	0.10(4)[a]
7.65	0.090(2)[b]	1.18(23)	0.85(11)	0.108(3)[b]	0.98(15)	0.88(13)	0.20(4)[b]
12.71	0.450(11)[c]	0.710(8)	0.662(26)	0.49(3)[c]	0.837(12)	0.687(26)	0.09(7)
15–16	0.6(2)	1.50(16)[d]	0.80(8)[d]				

[a] Literature values from [11].
[b] The values given are for the 7.654 MeV peak only and contributions from the ghost are omitted.
[c] Obtained by combining our experimental branching ratios.
[d] Proposed 2_2^+ state at 15.4 MeV [11].

gions we plot in Fig. 2 the inverse ft-value per energy bin and calculate from that the isospin asymmetry per energy bin. We see a small constant positive shift in favor of β^--decay similar in magnitude to those in Table 2. The asymmetry is seen to vary most in areas where the spectra change rapidly. These variations are mainly caused by differences in the amount of β summing due to different Q-values in the two decays. The energy independence confirms that the origin of the asymmetry is mainly nuclear structure [3,25] as a second-class-currents explanation infers an energy dependent asymmetry [3].

4. Theory

We have performed large-scale *ab initio* NCSM calculations for the relevant states of the $A = 12$ isotopes, i.e. the ground states of ^{12}B, ^{12}N, and the first few 0^+, 1^+, 2^+ $(T = 0)$ states of ^{12}C. In the *ab initio* NCSM approach all states are studied within a single framework without phenomenological fitting parameters. All calculations were performed using high-precision nuclear Hamiltonians from ChPT as described in [8] with and without 3NF added. The calculations are carried out in model spaces up to $6\hbar\omega$ and $8\hbar\omega$ respectively. In general, shell-model-like jj-coupled states are very well described whereas spatially extended states, such as the well-known 0_2^+ Hoyle state of ^{12}C, are significantly more difficult to accommodate in the finite harmonic-oscillator (HO) model space. The latter category of states is therefore characterized by slow convergence. These facts are illustrated in Fig. 3 that displays theoretical and experimental energy spectra of relevant $T = 0$ states in ^{12}C. The NCSM calculations with the ChPT interactions provide the correct level ordering with the exception of the 0_2^+ state and the experimental observation of broad cluster-like structures at 9–12 MeV. The addition of 3NF results in larger absolute binding energies. The experimental binding energy of ^{12}C is 92.16 MeV. The NCSM result in the largest model spaces reached in this study is 95.51 (81.56) MeV using ChPT NN + 3NF (NN only) interactions. The fully converged binding energy of ^{4}He using the same interactions is 28.6 (25.4) MeV [8,26]. The corresponding triple-alpha threshold is 9.8 (5.4) MeV. It should be noted, however, that the threshold position does not influence the NCSM results as all the states are artificially bound due to the use of HO basis. The 3NF also provides an increased internucleon spin–orbit interaction which is reflected in the anomalous lowering of the 1^+ state. Relative (excitation) energies are reproduced to within 1 MeV for most states. In addition, we note that the beta-decay Q-values are reproduced with at least the same precision.

The NCSM wave functions were used to compute Gamow–Teller transition strengths in the impulse approximation. In addition, effort was spent to quantify the rates of convergence by comparing results for different choices of HO frequency and model space. For the given observable, B_{GT}, the total error is estimated by $\Delta B_{GT} = (\Delta B^2_{GT,N} + \Delta B^2_{GT,\Omega})^{1/2}$, where $\Delta B_{GT,N}$ and $\Delta B_{GT,\Omega}$ represent the observed differences with respect to changes in model-space size and HO frequency, respectively. As an example, the convergence of the $B_{GT}(^{12}N)$ to the first 0^+ and 1^+ $^{12}C(T = 0)$ states are presented in Fig. 4 as a function of the model-space size. For each model space, the convergence-rate estimate ΔB_{GT} is shown as an error bar.

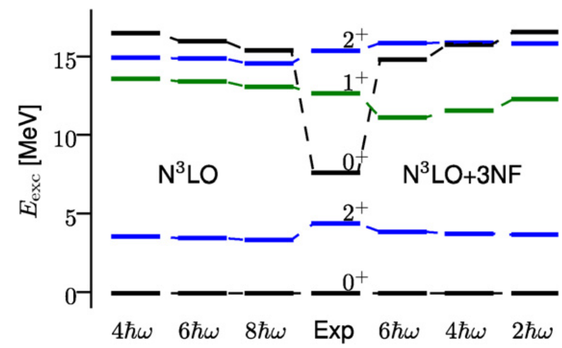

Fig. 3. Spectrum of $^{12}C(T = 0)$ states populated in Gamow–Teller beta decay from ^{12}B and ^{12}N, and for which B_{GT} values could be extracted in the present experiment (see Table 2). Experimental energy levels from [11] are compared to NCSM theoretical results obtained using ChPT interactions (N^{3}LO) with and without the 3NF. Results from calculations performed at different model spaces are shown.

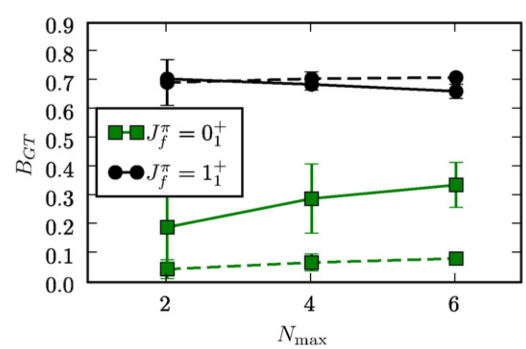

Fig. 4. Calculated $B_{GT}(^{12}N)$ to the first 0^+ and 1^+ $^{12}C(T = 0)$ states as a function of the model-space size. Calculations are performed using the ChPT interactions with (solid lines) and without (dashed lines) 3NF. Error bars represent the rates of convergence with respect to dependence on model-space size and HO frequency. See the text for details.

5. Discussion

In Table 2 the experimental B_{GT} values are compared to the results from the NCSM calculations. We observe a systematic improvement with experiment in calculations that include the 3NF.

This is particularly striking for transitions to the ground state. The importance of the 3NF for the ground state B_{GT} can be traced to the sensitivity of this particular transition to the magnitude of the spin–orbit interaction and the corresponding breaking of the SU(4) symmetry. This was already observed in earlier calculations with a different 3NF [1]. The calculated transition to the 1^+ 12.71 MeV state is in much better agreement with the present data that reduce the branching ratio by a factor of ≃2.5 compared to earlier measurements. It should be noted that the current NCSM calculations do not properly describe the 7.654 MeV state. The NCSM 0_2^+ state is at about twice the excitation energy of the 7.654 MeV state and the B_{GT} values are strongly overestimated. The alpha clustering must be taken into account to describe this state. The NCSM predicts a strong GT transition to the 2_2^+ state around 15–16 MeV with an experimental candidate at 15.4 MeV [11]. In Table 2 we have estimated the GT strength to the 15–16 MeV region by assuming a contribution from each bin in Fig. 2 calculated with the narrow level formula. A slightly lower value, within the quoted error, results from using the average f_β-value and the summed branching ratio for the 15–16 MeV region. The estimated 15–16 MeV GT strength matches the NCSM prediction when the 3NF is included. The isospin breaking due to the Coulomb and the strong force is included in the ChPT nucleon–nucleon interaction. Still, the experimentally observed asymmetries are not reproduced in the calculations as no coupling to the continuum is included and the employed ChPT 3NF is isospin invariant.

The GT strength in the β-decays of ^{12}N and ^{12}B has also been studied with phenomenological approaches. Using a derived effective interaction [27] for the 0p1sd shell-model (SM) space the GT strengths to the 0_1^+ (ground state), 2_1^+ (4.44 MeV), 0_3^+ (10.3 MeV) and 1_1^+ (12.71 MeV) states were calculated in Ref. [28]. Their B_{GT}-values are very similar to the NCSM NN + 3NF results. The 7.654 MeV (0_2^+) state was considered to be outside the 0p1sd model space, but in contrast to NCSM a 0^+ state in the 9–12 MeV was found in the model space. Note, however, that the experimental 10.3 MeV state was included in the list of states used to derive the effective interaction [27]. Using the antisymmetrised molecular dynamics (AMD) approach log ft-values for experimentally known states as well as suggested new ones are calculated in [9] for transistions from ^{12}N. Introducing built-in correlations this method is capable of combining cluster- and shell-model-like structures and should therefore pick up the states missed by SM approaches. The AMD calculations reproduce the GT strengths to the experimentally known states within a factor 2, including the 7.654 MeV state. It finds a 0_3^+ in the 9–12 MeV region with a factor 3 less strength than the 0_2^+, a 2_2^+ in the same energy region with a factor 100 less GT strength, and a 2_3^+ at roughly 13 MeV with about the same GT strength as the 2_1^+. In their energy spectrum there is also a 2_4^+ state in the same energy region as well as two 4^+ states and a 6^+ state. The first 1^+ states, however, appear at significantly larger energies. The low feeding to the 2_3^+ seems to be at variance with the experimentally seen strength in the 13–16 MeV region, while the existence of the 2_2^+ state can be in agreement with the data if the feeding is as low as suggested. This would also suggest that the strength seen in the 9–12 MeV region would be mainly 0^+. This brings back the question whether a 2^+ state exists in the 9–12 MeV region with its potential implications for astrophysics [4]. Recently there have been several experimental claims for unbound 2^+ states in ^{12}C in the 10–12 MeV region [29–31].

In [4,5] a fit to the 9–12 MeV region was presented which consisted of an interference between the 7.654 MeV 0^+ state and a higher lying 0^+ state around 12 MeV. This fit only included break-up of the populated states via the ^8Be ground state. Using the normalisation obtained in the present work the fit in [4,5] predicts branching ratios to the 7.654 MeV state of 5.2(8)% and 1.7(3)% for the ^{12}N and ^{12}B decay respectively. The branching ratios to the 7.654 MeV state measured here are lower than these predictions and therefore it is necessary to go beyond the fit published in [4,5]. First of all this requires an R-matrix description capable of including all decay channels of the populated states in ^{12}C as well as the absolute normalisation now available. This work is still in progress and will be reported elsewhere.

6. Conclusion

This work in a sense completes the experimental mapping of the β-decays of ^{12}N and ^{12}B. Feeding to the bound states was the object of detailed studies during the 70s and 80s and now the feeding to unbound states is brought to nearly the same precision. The updated branching ratios to the unbound states also lead to a slightly modified ground state branch.

The interpretation of the populated structures is challenging due to the presence of cluster structure in the states in this energy region of ^{12}C. By comparing to the NCSM we have elucidated how much can be understood from an *ab initio* model with a minimum of adjustable parameters and using state-of-the-art nuclear Hamiltonians from ChPT. We find satisfactory agreement for the bound states and for the 1^+ state at 12.71 MeV, and also find evidence for a strongly populated shell-model like state in the 15–16 MeV region. The broad structures in the energy range 9–12 MeV are not explained by the NCSM which indicates that these are caused by strongly clustered states in ^{12}C. In contrast, AMD calculations indicate the presence of both 0^+ and 2^+ states in this region, but that the 2^+ states are weakly populated in the β-decays of ^{12}N and ^{12}B.

We conclude that it is important to investigate this energy region with other experimental probes to further elucidate the presence of 0^+ and 2^+ states.

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